

Hadron spectrum and hadrons in the nuclear medium

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Abstract. Some recent developments in chiral dynamics of hadrons and hadrons in a medium are presented. Unitary schemes based on chiral Lagrangians describe some hadronic states as being dynamically generated resonances. We discuss how standard quantum many body techniques can be used to calculate the properties of these dynamically generated and other hadrons in the nuclear medium. We present some results for vector mesons (ρ and ϕ), scalar mesons (σ , κ , $a_0(980)$, $f_0(980)$), the $\Lambda(1520)$ and for the in-medium baryon-baryon interaction.

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1 Introduction

Coupled channels unitary models based on the chiral Lagrangians have provided a framework that allows to extend the calculations to higher energies than standard χ PT and have been very successful in the description of hadronic phenomenology. These models reproduce well meson-meson phase shifts up to energies above 1 GeV [1] and are able to generate a number of well established baryonic resonances like $N^*(1535)$, $\Lambda(1405)$, $\Lambda(1670)$, $\Sigma(1620)$, $\Xi(1690)$ and others [2, 3, 4, 5, 6]. These resonances appear dynamically as poles of the meson baryon scattering amplitudes. The analysis of the residues of the poles in the different scattering channels gives the couplings and branching ratios of the resonances.

An important problem in nuclear physics is the understanding of the properties of hadrons at finite baryonic densities. Many different theoretical approaches to this problem can be found in the literature. A quite interesting question is if the very special nature of the dynamically generated resonances obtained in chiral unitary models will have consequences for their in medium properties. It looks clear that this description of these particles has some implications. For instance, the $\Lambda(1405)$ appears in these models as a resonant state in $\bar{K}N$ and/or $\pi\Sigma$ scattering. The changes in the properties of the constituents \bar{K} , N , π , Σ will also change the results for their scattering amplitude and thus for its resonant states like the $\Lambda(1405)$.

The basic idea of the approach we present here is to start from these models which describe adequately the properties of several hadronic resonances in vacuum and their couplings to pseudoscalar mesons. Then, we incorporate nuclear medium effects by including vertex corrections and a suitable modification of the pseudoscalar meson and the baryon propagators, which can be done in terms of density dependent selfenergies. The selfenergies

are studied by means of a many body calculation accounting for their interactions with the nuclear medium. With this formulation we automatically consider the presence of additional decay channels which are not present in vacuum, since they require an interaction with one or more nucleons in the medium.

We will start discussing the π and K selfenergies. They experience a sizable renormalization at finite densities as a consequence of their interactions with the nucleons as it has been found in many theoretical calculations and experimental results. Then, using these selfenergies as ingredients, we study some medium effects on vector mesons (ρ and ϕ), dynamically generated scalar mesons (σ , κ , $a_0(980)$ and $f_0(980)$) and for the $\Lambda(1520)$ resonance. Finally, we will discuss briefly some recent results on the NN interaction in nuclear matter.

2 Pion and Kaons selfenergies in nuclear matter

The pion selfenergy in the nuclear medium at intermediate energies is relatively well known. It is mainly driven by its p -wave coupling to $p-h$ and $\Delta-h$ excitations as depicted in Fig. 1. Higher order terms obtained by the iteration of these excitations, considering also short range correlations, and the small contribution of s -wave scattering are also included in the calculations. Analytical expressions, as well as results can be found in Refs. [7]. In Fig. 2 we show the results for the pion propagator. Three wide peaks appear in its imaginary part corresponding to $p-h$ excitation, the pion peak that occurs at lower energies than in vacuum and $\Delta-h$ excitation respectively. This model has been widely tested and agrees well with pion-nucleus phenomenology from low to intermediate energies.

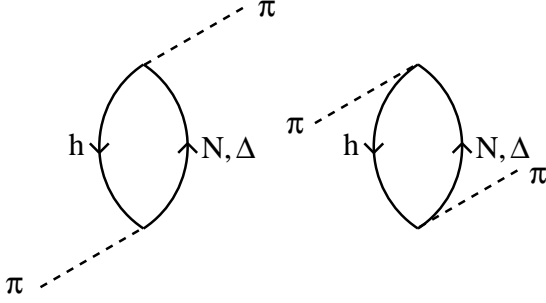


Fig. 1. Diagrams contributing to π selfenergy in the nuclear medium.

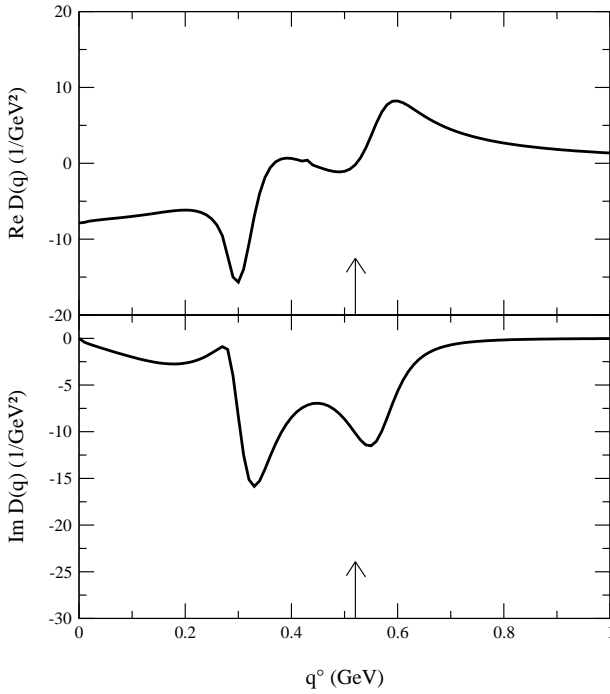


Fig. 2. Real and imaginary part of the π propagator at $\rho = \rho_0$ as a function of the energy for a pion with momentum $q = 500$ MeV. The arrow indicates the position of the pion pole in vacuum.

The kaon selfenergy is smooth at low energies and a simple $t\rho$ approximation can be used [8]. The situation is more controversial for the antikaons with recent experimental data that might be interpreted as very deep kaonic atoms [9, 10] suggesting very strong potentials, incompatible with the calculations based on chiral models, although alternative interpretations of these results have been presented [11]. See also Ref. [12] and references therein.

The model used in what follows is based on the chiral unitary model in coupled channels for the s-wave $\bar{K}N$ scattering of Ref. [13]. This model is quite successful in the description of many observables, like threshold ratios of K^-p to inelastic channels and K^-p cross sections in the elastic and inelastic channels. A selfconsistent calculation of the selfenergy in the nuclear medium was later carried out in Refs. [14, 15] and includes the p-wave excitation of Λh , Σh and $\Sigma(1385)h$. The results of these works show

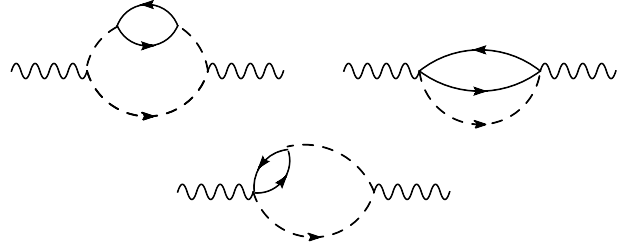


Fig. 3. Diagrams contributing to ρ selfenergy in the nuclear medium.

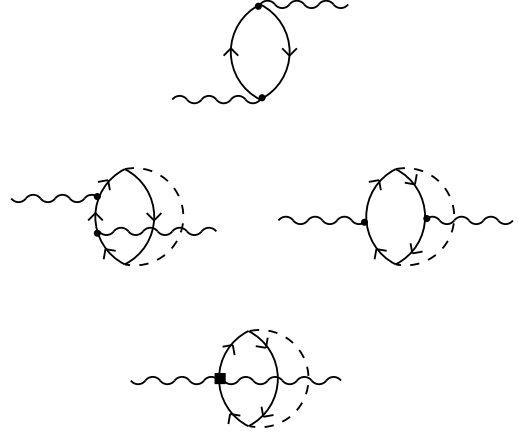


Fig. 4. Other diagrams contributing to ρ selfenergy in the nuclear medium.

an antikaon spectral function quite wide at normal nuclear densities and with the peak displaced toward low energies. The optical potential from Ref. [14] also compares well with kaonic atoms data [16] although other phenomenological potentials with a much deeper attraction also show a good agreement [17].

3 Vector mesons (ρ and ϕ)

In medium properties of the ρ meson have been extensively studied [18, 19, 20, 21, 22, 23, 24, 25, 26] after some predictions of scaling laws implying strong droppings of the ρ meson mass even at normal nuclear density. On the other hand, this mass reduction could be observed through the vector meson leptonic decays, free from strong final state distortions. Here, we will briefly present our approach to this topic.

The ρ meson decays in vacuum into two pions. The large modification of the pion properties in nuclei discussed in the previous section implies changes of the ρ properties, i.e., in the medium new decay channels are open because of the coupling of pions to baryon-hole excitations, see Fig. 3. Other new decay channels appear because of the direct coupling of the ρ to the nucleon, sometimes producing some baryon-hole excitation, as shown in Fig. 4. In particular, the excitation of the $N^*(1520)$ is very relevant. The contribution of these and other pieces is done using standard many body techniques. Details can

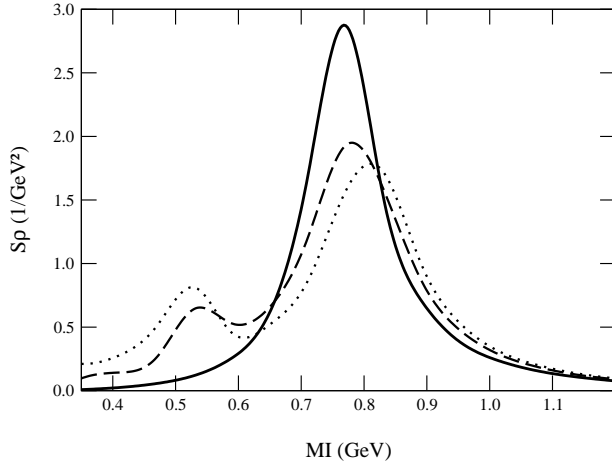


Fig. 5. ρ spectral function in vacuum: solid line, for $\rho = \rho_0/2$; dashed line and for $\rho = \rho_0$: dotted line.

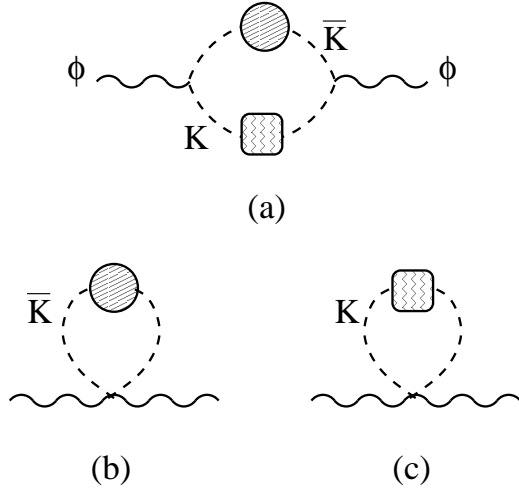


Fig. 6. Diagrams contributing to ϕ selfenergy.

be found in Refs. [27,28]. The obtained spectral function is depicted in Fig. 5. Although some strength appears at low masses, due to the coupling to $N^*(1520)$, and there is some widening, the ρ peak moves very little toward a mass higher than in vacuum. This is in contrast with popular dropping mass scenarios. Several microscopic calculations have obtained very similar results [29,30] which seem to have been confirmed by recent experimental data [31] when compared with various theoretical approaches [32].

The ϕ meson in medium properties have been studied along similar lines in Refs. [8,33]. The ϕ decays primarily in $K\bar{K}$ and in the medium the kaons have an spectral function quite different from vacuum, as discussed previously. The consideration of these effects, depicted in the diagrams shown in Fig. 6, leads to a width one order of magnitude larger than in vacuum and also to some small mass reduction. In [34], the loss of flux in photoproduction reactions was proposed as a possible experimental test of the model, see Fig. 7. Later experiments [35] have

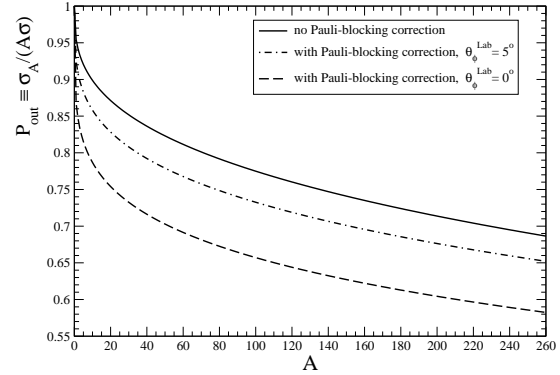


Fig. 7. Ratio of Nucleus to A times nucleon cross sections, $\sigma_A/(A\sigma)$, for ϕ production as a function of A ($p_\phi = 2\text{GeV}$)

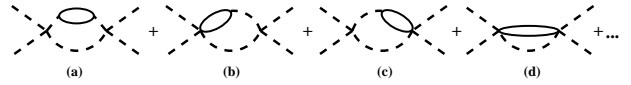


Fig. 8. Diagrams contributing to meson meson scattering in the nuclear medium.

confirmed the importance of medium effects suggesting a ϕ width even larger than expected that might indicate a very large ϕN cross section [36]. The small reduction of the mass has also been confirmed recently [38] although a detailed comparison of the theoretical models with data is still to be done.

The theoretical study of the ω meson in the medium is technically more complex due to its strong coupling to three-body channels although its narrow width makes it very well suited for experimental observation. Recently, the CBELSA/TAPS Collaboration has published some interesting results showing medium effects on the ω meson [37]. A possible explanation of the data is the reduction of the ω mass. Other possibilities related to final state interactions of the detected π^0 are currently being studied.

4 Scalar mesons (σ , a_0 , f_0 and κ)

One of the major successes of chiral unitary models is the description of meson-meson scattering amplitudes up to energies above 1 GeV. Some resonances appear that can be identified with the a_0 and f_0 mesons. Much further from the real axis appear the poles corresponding to the σ and κ mesons. The medium modifications of these resonant states can be obtained calculating meson meson scattering but now including the proper in medium selfenergies of the mesons as depicted in Fig. 8, apart from some vertex corrections that produce only minor effects.

The properties of the σ meson in medium are of particular interest because of theoretical predictions claiming that at normal nuclear densities it could become much lighter and narrower, due to chiral symmetry restoration, and also because of some experimental results [39,40] showing an enhancement of two pion production in the isoscalar channel at very low invariant masses that might be due to the in medium σ meson. Indeed, in chiral unitary models

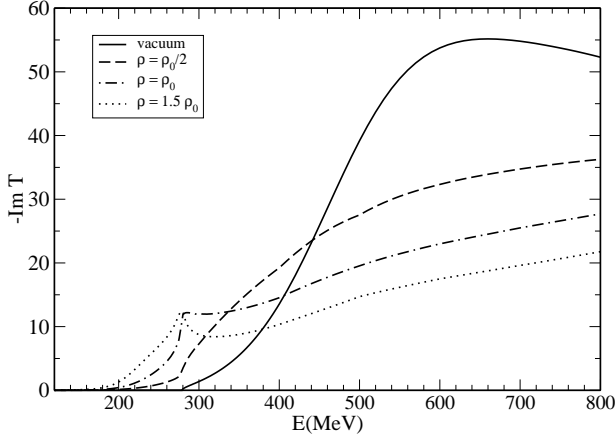


Fig. 9. Imaginary part of the pion pion scattering amplitude in the σ channel at several densities.

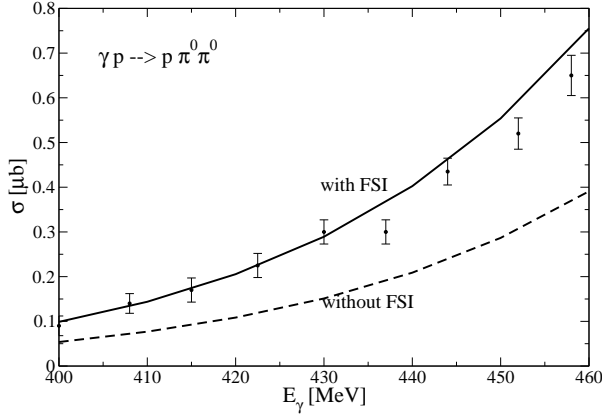


Fig. 10. Cross section for $2 \pi^0$ photoproduction in nuclei as a function of the energy with and without final state interaction between the two pions in the $I=0$ channel. Experimental points from Ref. [44].

the σ spectral function has a large enhancement at low masses [41], see Fig. 9 where the imaginary part of the $\pi\pi$ scattering amplitude is shown. This enhancement is related in these models to the position of the σ pole that at $\rho = \rho_0$ appears at low mass and closer to the real axis [42]. The calculation of two pion photoproduction making use of these techniques for the nuclear effects and starting from a good microscopical model for the reaction in vacuum, has found good agreement with experiment [43] for both total and differential cross sections.

However, the presence of additional medium effects makes difficult the isolation of possible σ effects [45,46], which are small due to the low effective density of these processes. Nonetheless, these results together with those studying pion induced two pion production [47,48] support the possibility of testing the calculations when experiments with better statistics and for heavier nuclei are carried out.

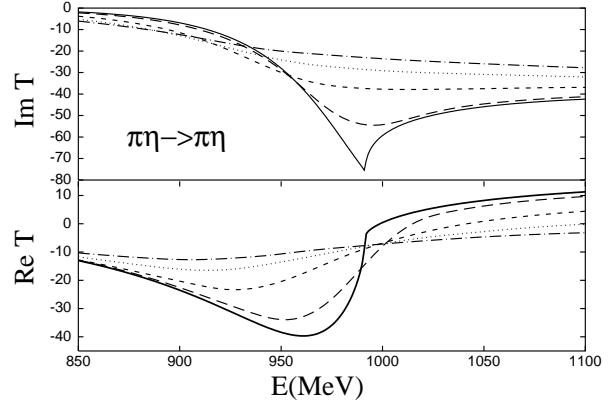


Fig. 11. Real Imaginary part of the $\pi\eta$ scattering amplitude in the $I=1$ channel at several densities. Solid line, free amplitude; long dashed line, $\rho = \rho_0/8$; short dashed line, $\rho = \rho_0/2$; dotted line, $\rho = \rho_0$; dashed dotted line, $\rho = 1.5\rho_0$.

Also interesting is the case of the κ and $\bar{\kappa}$ that because of the different interaction of kaons and antikaons with the medium get a different mass[49]. The large attraction that the nucleus exerts over the pions makes these resonances lighter and also narrower. However, they do not become as narrow as to be clearly visible experimentally. Nonetheless, these results are very sensitive to the strength of the antikaon potential so controversial nowadays. If very deep antikaon potentials were confirmed that would automatically imply the existence of a low mass narrow $\bar{\kappa}$ in nuclei. In addition to the κ pole positions, also the $K\pi$ and $\bar{K}\pi$ s-wave scattering amplitudes at finite densities were studied. Strong modifications were found for both channels that also became different although they are equal in vacuum. The most noticeable effect is a peak found at low invariant masses of the $K\pi$ system that could be observed experimentally in reactions where a s-wave low energy $K\pi$ pair is produced.

Other dynamically generated mesons like the a_0 and f_0 have also been studied theoretically using the same method in Ref. [50]. These two resonances are relatively narrow and couple strongly to the $K\bar{K}$ channel. A large growth of their widths was obtained but without relevant changes in their masses. As an example, we show in Fig. 11 the $\pi\eta$ scattering amplitude. Whereas in vacuum there is a peak, related to the $a_0(980)$ pole, in medium, even at low densities the peak practically disappears.

5 Baryons

We will discuss first the case of the $\Lambda(1520)$ which is generated from the s-wave interaction of the decuplet of $3/2^+$ baryons with the octet of pseudoscalar mesons[51,52]. For a better description, the inclusion of the KN and $\pi\Sigma$ d-wave channels was also required to get a good agreement on the position of the peak and the width of the resonance[53,54], see Fig. 12.

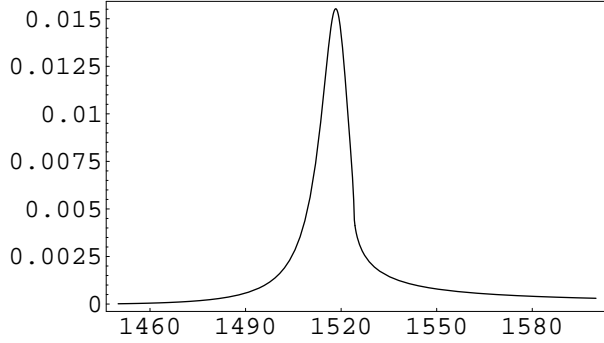


Fig. 12. $|T_{\bar{K}N \rightarrow \pi \Sigma^*}|^2$ in units of MeV^{-2} showing the $\Lambda(1520)$ peak.

Its relatively small width makes this resonance suitable for the experimental verification of the predicted medium effects.

In vacuum, $\Lambda(1520)$ couples strongly to the $\pi \Sigma^*(1385)$ channel, even when the decay is largely suppressed because of the small phase space. However, in the nuclear medium, this decay channel is much enhanced due to both the pion and $\Sigma^*(1385)$ selfenergies, leading to a predicted width ~ 5 times larger than in vacuum at normal nuclear matter densities [55]. This large effect could be observable experimentally, studying the A -dependence of $\Lambda(1520)$ production reactions [56].

As mentioned above, the antikaon in medium self-energy was calculated in a self-consistent way in Ref. [15]. This also implies the study of medium effects of several hyperons relevant for the calculation. Their results show a downwards shift for the Λ and Σ masses of ~ 30 MeV at normal nuclear density and a large enhancement of the Σ^* width. The dynamically generated $\Lambda(1405)$ is strongly diluted at $\rho = \rho_0$ and remains only as a small bump close to its vacuum position.

6 In medium baryon baryon interaction

The scalar isoscalar channel is a very relevant part of the nucleon nucleon interaction, basically mediated by the exchange of two correlated (" σ ") or uncorrelated pions. The σ part of the channel is strongly modified in the nuclear medium, as shown in a previous section, and this could lead to some effects on the NN interaction in the medium. This topic was analyzed in Ref. [57]. The corrections for the NN interaction in the medium were found to be sizable, see Fig. 13. We also found that short range correlations are fundamental to produce only moderate changes. Further studies are still required to analyze the stability and properties of nuclear matter with potentials incorporating these results.

The central part of the ΛN and $\Lambda \Lambda$ potential has also been studied including the correlated, which in this case involves both σ and κ , and uncorrelated two-meson exchange [58]. We find a short range repulsion generated by the correlated two-meson potential which also produces an

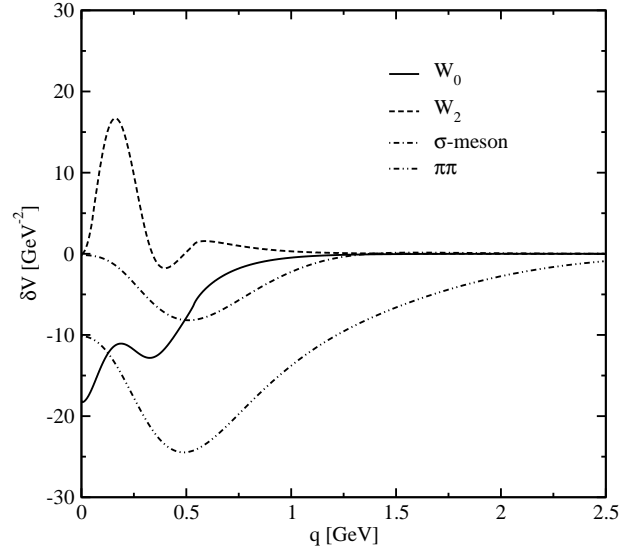


Fig. 13. Modification of the NN interaction at normal nuclear matter density in momentum space. Solid line: central part of OPEP, dashed line: tensor part of OPEP, dot-dashed: correlated σ -meson exchange and dot-dot-dashed curve: uncorrelated $\pi\pi$ exchange.

attraction in the intermediate distances region. This interesting feature cannot be reproduced by the exchange of a σ meson. The uncorrelated two-meson exchange produces a sizable attraction in all cases.

7 Conclusions

In this work we have presented some recent results on the study of hadron properties. The use of χ PT to incorporate low energy constraints on the scattering amplitudes and of coupled channels unitary models which generate dynamically meson and baryon resonances provides a suitable framework to study nuclear medium effects on those generated resonances. These medium effects are considered using standard techniques of many body Quantum Field Theory. In this approach, we have shown results for several scalar mesons: σ , κ , $a_0(980)$ and $f_0(980)$ and for some baryonic resonances like $\Lambda(1520)$ and $\Lambda(1405)$ and also for the controversial antikaon optical potential. Some of the results presented here already have good experimental support and others will soon be tested.

We have also discussed the scalar isoscalar part of the nucleon nucleon interaction and how this piece, partly mediated by the σ , is strongly modified in a nuclear medium. It must be considered that in our approach the σ is only a resonant two pions state and the interaction resulting from the exchange of this resonance cannot be fitted by a single meson exchange.

Finally, the pion and kaon in medium selfenergies have important consequences for the decay of vector mesons that have also been analysed with our methods providing an alternative picture to other calculations. We find

quite small mass changes, consistent with many experimental data, but large width enhancements and even complicated spectral functions with several bumps produced by the strong coupling of the vector mesons to some particular excitation mode. This shows the need of detailed microscopic calculations that properly take into account the relevant degrees of freedom in the nuclear medium.

8 Acknowledgments

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